THE CASSINI / HUYGENS MISSION TO SATURN AND TITAN

(IAF-00-Q.2.02)

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Abstract

Cassini/Huygens is a joint United States NASA , European Space Agency, and Italian Space Agency mission to Saturn to perform a detailed investigation of the Saturnian system, including Saturn's rings, magnetosphere, atmosphere, and internal structure, as well as to study Saturn's large moon Titan and the numerous smaller icy satellites. Huygens is the name of the ESA provided atmospheric probe that will enter the atmosphere of Titan, descend to the surface, and return scientific data to the Cassini orbiter passing overhead. The combined Cassini Orbiter and Huygens Probe spacecraft was launched on 15 October 1997, and is now well into its third year of flight on its nearly seven year trajectory to Saturn.

Because of the long transit time from launch to arrival at Saturn, a substantial development effort covering flight and ground software and the design of operational plans and processes is being implemented during the cruise phase. In addition, a fairly active plan of instrument and engineering subsystem maintenance, instrument checkout and calibration, and the return of science data where opportunities exist has made the cruise phase of the mission a very busy and productive one.

This paper summarizes the principal accomplishments of the Cassini/Huygens mission over the past year, which include a complete reload of the flight software on the spacecraft, including that of most of the orbiter science instruments, the final definition of the exact orbital tour to be flown at Saturn, and considerable progress in designing the sequence of science observations to be made in the tour. The activities leading to completing the science plan prior to arrival at Saturn in '04 are presented in detail. Another significant event, the flyby of Jupiter in December, 2000 for the final gravity assist needed on the way to Saturn, and the planned science observations during this encounter, are described.

Introduction

A fairly detailed description of the Cassini/Huygens mission and spacecraft was given at the 1999 IAF Conference, and is documented in reference 1. This current paper focuses primarily on the events and activities of the mission over the past year since that time, and describes near-term future plans. The past year has been a busy and productive one for the Cassini/Huygens Program. The primary activity continues to be that of preparation for the mission at Saturn, commencing somewhat prior to the arrival on July 1, 2004. The plan since well before launch had been to focus the pre-launch effort on what was essential to ensure a successful launch of a well designed, built, and tested spacecraft, and leave the development of much of the ground system, some flight software, and the science planning and preparations for the mission at Saturn for the nearly seven year period between launch and Saturn encounter. This effort continues to be the principal task of the project. Preparations for the upcoming flyby of

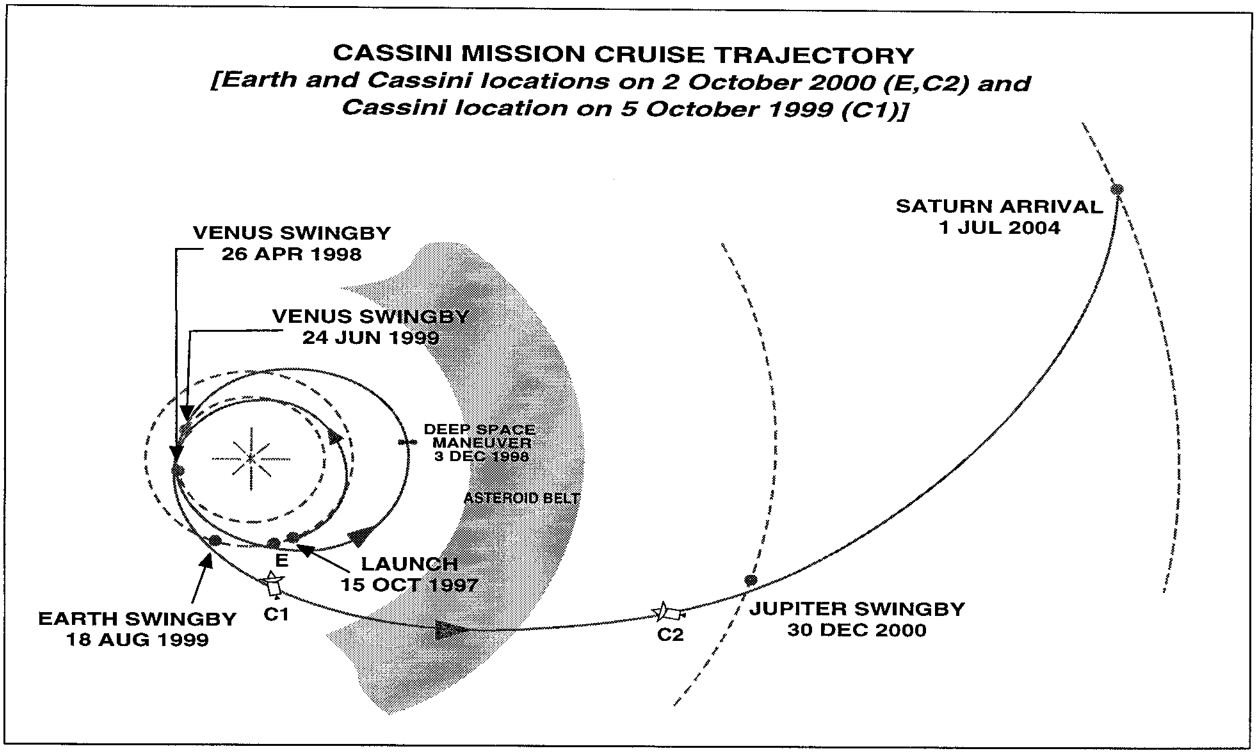

Figure 1: Cassini Mission Cruise Trajectory

Jupiter - closest approach occurs on December 30 of this year - also constitute a significant effort over the past year. Plans are based on using the current flight and ground software and ground system tools and processes being developed for the Saturn mission during this Jupiter encounter for the purpose of testing the software and tools and training of the flight team. This will provide a validation of the plans and designs being developed, as well as providing a real in-flight opportunity for lessons learned to be incorporated into the remainder of the effort between Jupiter and Saturn. Jupiter science data collected during the process will be a very substantial bonus as well, especially considering the unique opportunity to do simultaneous two-spacecraft observations at Jupiter based on a cooperative effort with the Galileo Project. A considerably smaller effort that has occupied the team over the past year has been the ongoing operation, maintenance, and navigation of the spacecraft. These activities have been largely routine, and the spacecraft continues to operate flawlessly.

Current Mission Status

The Cassini/Huygens spacecraft has traveled the majority of the arc length along its path from the Earth flyby to its Jupiter encounter during the past year. After its gravity boost from Earth on August 18, 1999, the spacecraft crossed Mars' orbit on September 25, 1999, entered the asteroid belt in mid-December, completed its pass through the belt in mid-April, 2000, and currently is nearing Jupiter, as shown in figure 1. Cassini is the seventh spacecraft to pass through the asteroid belt, all of which did so without any harm. Although the potential for a damaging collision is greater in the belt than elsewhere in the solar system, the ratio of the volume of material to the total volume of space within the belt is very small number, so the safe passage was the fully expected outcome.

For the first part of the mission, while the spacecraft was still in the inner part of the solar system, it was necessary to keep the high-gain antenna pointed to the sun in order to shade the spacecraft and keep temperatures within the required bounds. However, now that Cassini is moving to the outer part of the solar system, with the range to the sun increasing monotonically until it reaches Saturn, and the angle between Earth and the sun as seen at the spacecraft becoming smaller, it is now possible to operate safely with the high-gain antenna continuously on Earth point. This condition has existed since February, 2000, and has greatly facilitated communications with the spacecraft because of the much higher data rates enabled by the use of the high-gain antenna. Nearly continuous science data from the fields and particles instruments, as well as the Cosmic Dust Analyzer instrument, have been collected since going to the HGA.

Navigation

Navigation of the Cassini/Huygens spacecraft over the past year has been very routine and uneventful, fortunately for the Navigation Team, because they also have a very challenging task to accomplish in order to develop the degree of planning and automation that is going to be required to navigate the spacecraft along its planned path in orbit at Saturn. That activity will be far from routine and uneventful! The first post-Earth Trajectory Correction Maneuver (TCM), TCM-13, was performed on August 31, 1999, with a delta-V of 6.7 m/sec, for the purpose of correcting for the effects of the small statistical dispersions associated with the delivery of the spacecraft to the Earth flyby target. The only other TCM performed this past year was TCM-14, performed on June 14, with a delta-V of 0.56 m/sec. This correction compensated for the nearly negligible delivery errors resulting from TCM-13, as well as accomplishing a small adjustment in the Jupiter target conditions to achieve a 2000 km flyby of the Saturnian satellite Phoebe about three weeks prior to Saturn Orbit Insertion (SOI). The original propellant-optimal approach trajectory provided a 56,000 km flyby of Phoebe, but considering that Phoebe is a target of relatively high scientific interest, and that Cassini never gets as far from Saturn as Phoebe is once it is in orbit about Saturn, a recent Program decision was made to accomplish the closer satellite flyby at a propellant cost of 27 m/sec.

The outcome of TCM-14 is shown in figure 2, indicating the Jupiter relative target point and its associated *a priori* delivery statistics, and the current estimate of the achieve flyby trajectory and the statistics characterizing the uncertainty in this estimate.

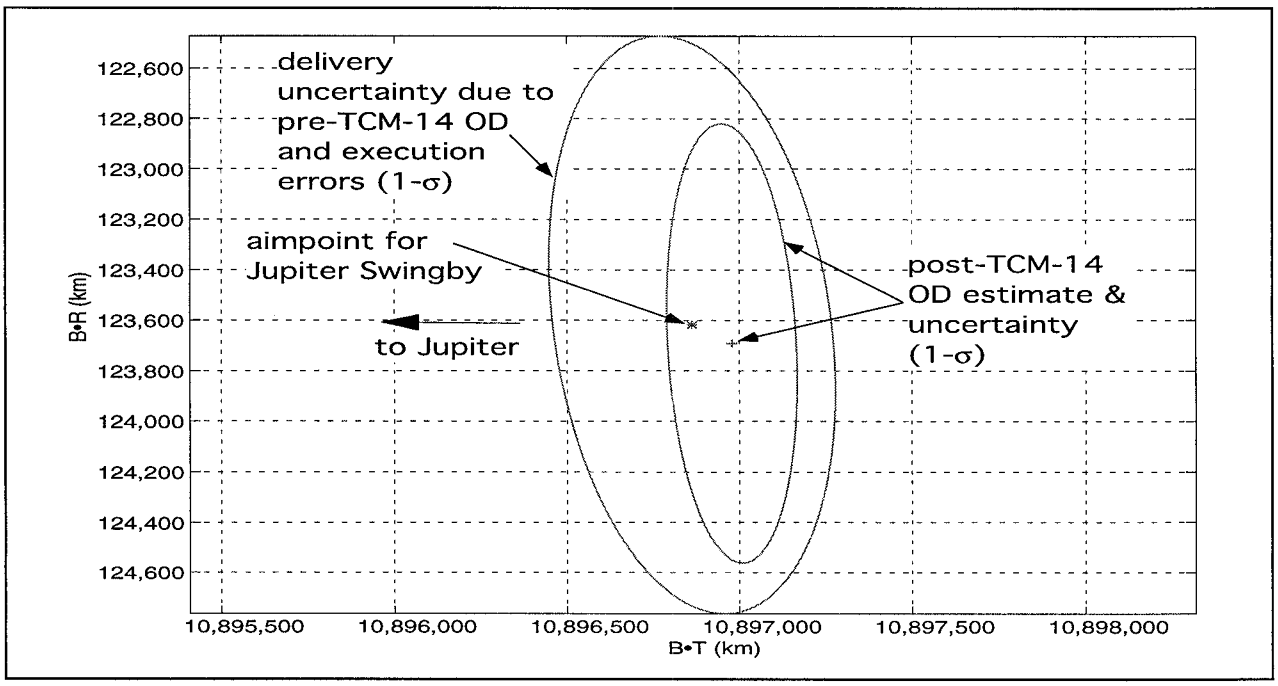

Figure 2: Post TCM-14 Trajectory

Two additional TCMs that had been scheduled prior to the Jupiter encounter in the event that they were needed have been canceled, so no additional maneuvers are required until well after the Jupiter flyby. The next one will be TCM-17 (canceled maneuvers keep their name designation, so maneuver numbers are not indicative of how many maneuvers have been done at any point in the mission) which is scheduled for March, 2001. This date is driven more by propulsion system maintenance requirements than by navigational needs.

Asteroid Image

On January 23, 2000, Cassini turned to point its Optical Remote Sensing instruments at the asteroid Masursky, with one of the resulting images shown in figure 3. At a distance of approximately 1,600,000 km, and a body diameter of approximately 15 to 20 km, the value of the imaging activity is perhaps greater for engineering purposes than scientific. Still, new scientific information was obtained on the asteroid's size, reflectivity, type, and rotation rate. Some of the streaks and point-like sources in this 6 mrad frame are in fact the images left by cosmic rays which hit the camera's CCD. This activity was the first time in flight that the autonomous onboard target tracking capability of the spacecraft had been used, and the fact that a number of images taken over a 1.5 hr span were captured in the 6 mrad field-of-view (fov) of the narrow angle camera is evidence that this capability worked well. However, the fact that the asteroid is near the edge of the fov, and that some images taken fell just outside of the narrow angle camera's fov (as determined by their location in the wide-angle camera fov), is the basis for further analysis to improve overall instrument targeting performance. With only a 3 mrad angle subtended between the narrow-angle camera's boresight centerline and the edge of the fov, very accurate instrument targeting is necessary to enable high resolution imaging of specific features on a target body. The Masursky images were taken on thruster based attitude control, because the Reaction Wheel Assembly (RWA) attitude control capability was not yet available. All imaging from this point forward is planned to be done while on RWA control, and improved knowledge of where the actual camera boresight is in spacecraft coordinates will also improve instrument pointing performance. Observations of the star Fomalhut scheduled for September, 2000, will provide an opportunity for verification of improvements expected in pointing accuracy.

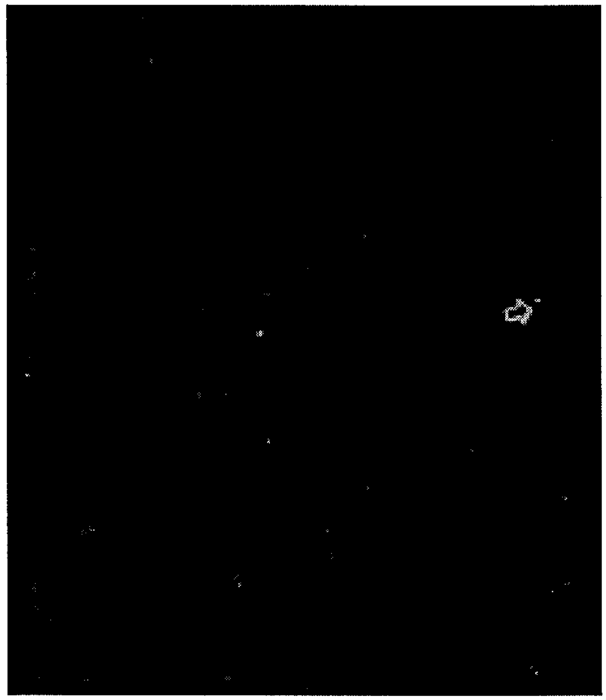

Figure 3: Narrow Angle Masursky Image

Flight Software Update

During this past year, complete new flight software loads have been loaded onto the Command and Data Subsystem (CDS), the Attitude and Articulation Control Subsystem (AACS), and on most of the twelve orbiter scientific instruments. The AACS flight software was loaded in March, 2000, with the primary new capability being the ability to use the Reaction Wheel Assemblies (RWA). The Cassini spacecraft was designed to perform attitude control using either the small thrusters using hydrazine, or the RWAs. The software delivered at launch did not contain the complete and tested capability to use the RWAs, and so the thrusters had been used to this point in the mission. The RWAs' primary advantages are that they provide a considerably more stable attitude control for improved Radio Science and remote sensing observations, and they use less hydrazine than the thrusters in performing the attitude control function. However, hydrazine usage is not eliminated because the thrusters are still used as needed for unloading the momentum that accumulates in the wheels. Currently this function is performed approximately once per week, with the expectation that this frequency will decrease. The primary source of torque imbalance leading to momentum buildup is solar pressure acting on the non-symmetrical spacecraft, so the rate of momentum buildup will decrease as the range from the sun increases with time.

Other AACS capabilities incorporated in this load include additional options for specifying targets for instrument pointing, additional star identification algorithms for star-based attitude estimation, a number of engineering changes requested based on in-flight operations experience, and fixes to known problems.

The CDS flight software was sent to the spacecraft in late July, and was loaded in CDS memory and made prime for spacecraft control on August 9. The two principal new capabilities enabled by this new load were Solid State Recorder (SSR) management, to enable and make more efficient the processing and handling of large volumes of data and special processing for high priority data, and several new telemetry modes, both for recording on the SSRs as well as for downlink of telemetry to Earth. Additional new capabilities include engineering change requests to improve operability based on inflight experience and the correction of some known problems.

The process of replacing the controlling software on the spacecraft's principal computer is potentially a risky one, and one that must be executed cautiously. The CDS had been operating on software identified as Version 5 since launch, and the current load is known as version 7. A
Version 6 was also developed and tested, but served as an interim step in developing Version 7, and was never sent to the spacecraft. Version 7 was uplinked to the spacecraft on July 28 and stored redundantly on the SSRs while Version 5 continued to operate on both strings of the CDS. On August 4, Version 7 was loaded on CDS string A, which was configured as the on-line, or backup, string. A set of preliminary tests was executed on Version 7 to verify its readiness for the purpose of controlling the spacecraft. On August 9th, the CDS A String was commanded to become prime and assume operation of the spacecraft for the first time, with CDS B still running Version 5 as a "hot" backup. On August 19th, Version 7 was loaded into the CDS B String
to make the spacecraft then fully operational on Version 7 flight software. Version 5 software will remain on the SSR for about 6 months as a backup in the event that any serious problems are discovered with Version 7 as more operating time is accumulated.

As of this writing, both subsystems are fully operational on their new flight software and all indications are that the performance is flawless. The Jupiter observing sequences which commence in October will exercise the entire system to a fairly considerable extent, and will provide an excellent verification of the software design and implementation to support the mission at Saturn.

Instrument Flight Software

During the past year, most of the Principal Investigator and Facility Instrument teams have updated their instrument FSW at least once in order in preparation for the instrument checkout (ICO) period this past summer and for the upcoming Jupiter flyby in December. CAPS, CDA, CIRS, MAG, MIMI, RPWS, UVIS, and VIMS made scheduled FSW deliveries in March and April. The usual reasons for the updates are to correct problems discovered during earlier operational periods, and to extend instrument capabilities for future operations. Examples of recent FSW updates have been: changes to the command executive and command sequence tables; addition of a new telemetry rate and new instrument expanded blocks (IEB); addition of on-board checking of check-sums; addition of an easier process for uploading IEBs; change to the command format for data-taking; and addition of high resolution imaging modes and a new data sampling mode. Of those instrument teams that did not deliver new loads during this period, INMS has not been operating, so was not scheduled to update their software. RSS does not have FSW. ISS, RADAR, and the Huygens Probe instruments currently have no plans to update their FSW throughout the life of the mission. The next scheduled software uploads are in early 2002 in preparation for Science Cruise activities later in the year.

Instrument Checkout

In January, 1999, a compressed period of instrument checkout and calibration was conducted, but was necessarily limited in scope because, in order to acquire the needed telemetry to accomplish the task, it was necessary to do it with the HGA pointed to Earth, and this was only permissible during a short time around opposition when the off-sun angle that resulted from pointing to Earth was small enough that the spacecraft was still shaded adequately to provide thermal protection. In order to complete some checkout and calibration objectives that were not able to be accomplished in this period, as well as to better characterize in greater detail many of the instruments' performance, a second instrument checkout period (ICO-2) was scheduled for the summer and early fall of 2000, where the activities could be performed at a more leisurely pace because the HGA was routinely on Earth-point. Also, the RWA capability enabled by the new AACS flight software permitted some activities to be done that were not previously feasible using the reaction control thrusters. Figure 4 shows a high level timeline of the various activities performed during this time. A hiatus was declared for approximately the month of August to accommodate the uplink, installation, and validation of the new CDS flight software load. The remainder of the ICO-2 activities were completed using this new software. spacecraft.

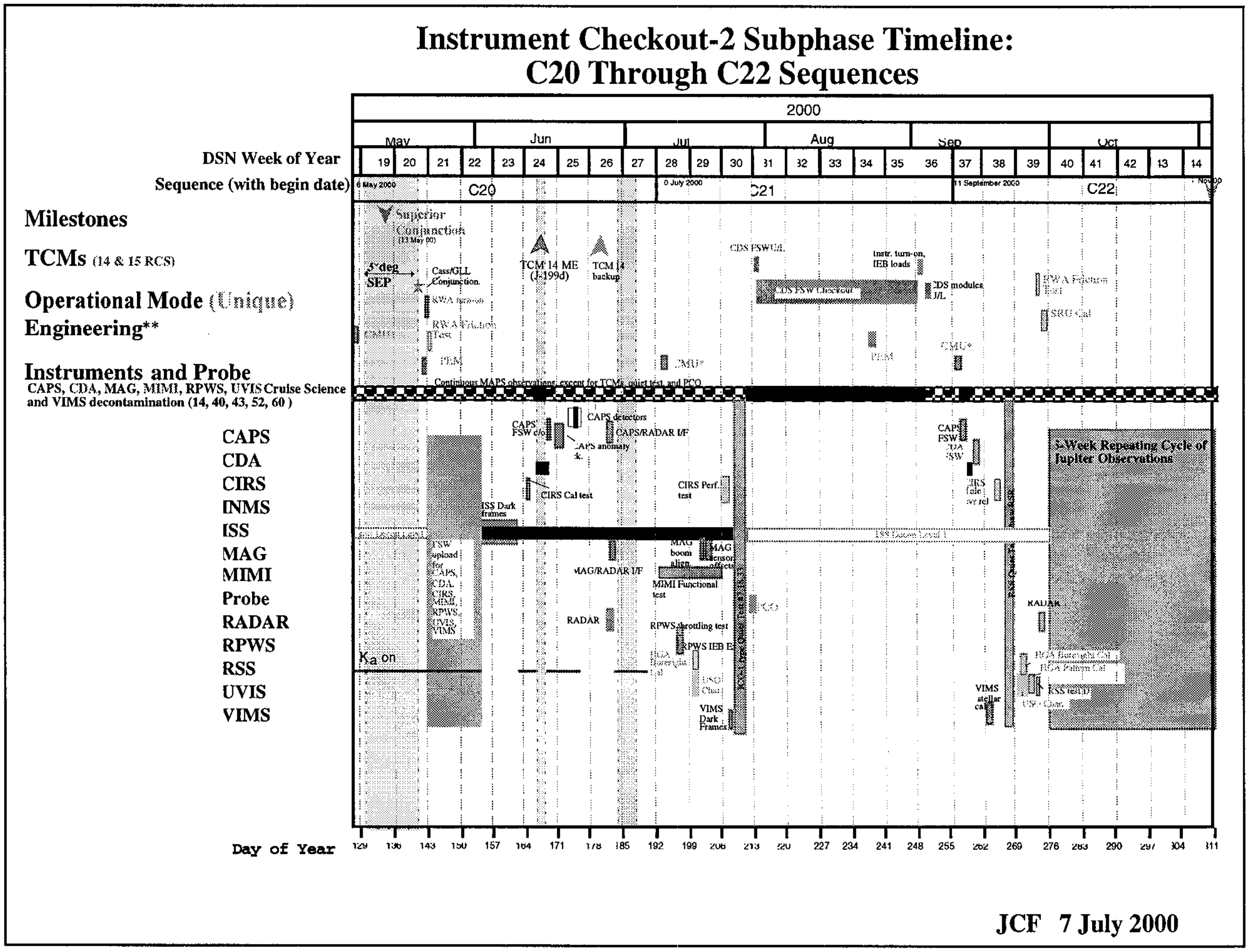

Figure 4: Instrument Checkout-2 Subphase Timeline

A number of objectives were accomplished with this effort. Over the three years since launch, the instruments have been used only very minimally, partly for lack of targets of scientific interest, and also because the Program's resources have been mainly dedicated to the effort of preparation for the mission at Saturn. So the operation of the instruments in this time period provided the opportunity to better characterize instrument performance in an environment similar to what will be experienced at Saturn and could not be duplicated on Earth pre-launch, as well as to determine any changes in instrument characteristics from before launch. Another objective that was only partially accomplished in the instrument checkout period in 1999 was the measurement of interference that might occur between various of the instruments. To determine this, a "quiet test" was developed where the instruments were placed in a quiescent "listen only" mode, and then each instrument in turn went through the complement of its activities and the others noted whether any noise or spurious signals were detected. Analysis to date has not indicated any interferences of any significant concern, but the results of this activity will at least provide the opportunity for instruments to time phase their activities or be able to identify and calibrate out spurious signals if interferences are determined to be present.

The Jupiter Encounter

Cassini's encounter with Jupiter on December 30, 2000, will be the fourth and final planetary flyby on its circuitous path to Saturn. It will also be the last of the four planetary gravity assists that were required in order to obtain the necessary energy to carry this large spacecraft on a path reaching to the orbit of Saturn. The final gravity boost required from Jupiter is small, at least relative to the capability offered by this massive planet, and hence Cassini will pass by at a distance of nearly 10 million km. Still, a sun relative speed change of 2.2 km/sec is achieved, exactly that required to reach Saturn in July, 2004.

A unique opportunity arising from the Jupiter flyby comes from the fact that the Galileo spacecraft is currently in orbit at Jupiter, and in spite of the fact that it has received a radiation exposure well beyond its design margin, it is performing well, and has a high likelihood of continuing to function during the Cassini flyby in December. For the period of time up to and for a while after Cassini's closest approach to Jupiter, Galileo will be near its perijove, deep within Jupiter's magnetosphere, while Cassini is relatively distant from Jupiter, but more importantly, Cassini will still be outside of Jupiter's magnetosphere. This provides an opportunity of considerable interest to the scientific community in that Cassini will be able to measure the solar wind environment unaffected by the magnetosphere while Galileo will be able to make *in situ*measurements of how the magnetic field responds to the now measured solar wind impinging on it. Beginning some time well after Cassini's closest approach, Cassini will have moved into the distant magnetotail region while Galileo will be outside the magnetosphere, approaching its apojove on a large orbit now rotated well away from the magnetotail direction. At this point, the two spacecraft will swap roles, but continue to study the solar wind/ magnetosphere interactions.

Another joint Galileo/Cassini observation will be measurements of the same beam of charged dust particles coming from Io around the time of Cassini's closest approach. Correlating the variations in the beam as seen by the two spacecraft at quite different positions will allow a first ever determination of the dust velocity distribution. The realization that Io is the source of these dust particles is a finding made by Galileo earlier in its mission. The dust detection instruments on the two spacecraft are similar in function and design, with the Cassini instrument having more recent technology and particle composition determination capability. Both instruments are designed, built, and operated by the same Principal Investigator.

Figure 5 shows a sketch of the sun-relative orbits of Jupiter and Cassini, with indications of where various of the Jupiter observations are being made. Also indicated are the approximate locations of Cassini when various of the planned Galileo observations will be made.

Figure 6 shows the Jupiter-relative orbits of Galileo and Cassini during the encounter period, ranging from 1 October, 2000, to 31 March, 2001.

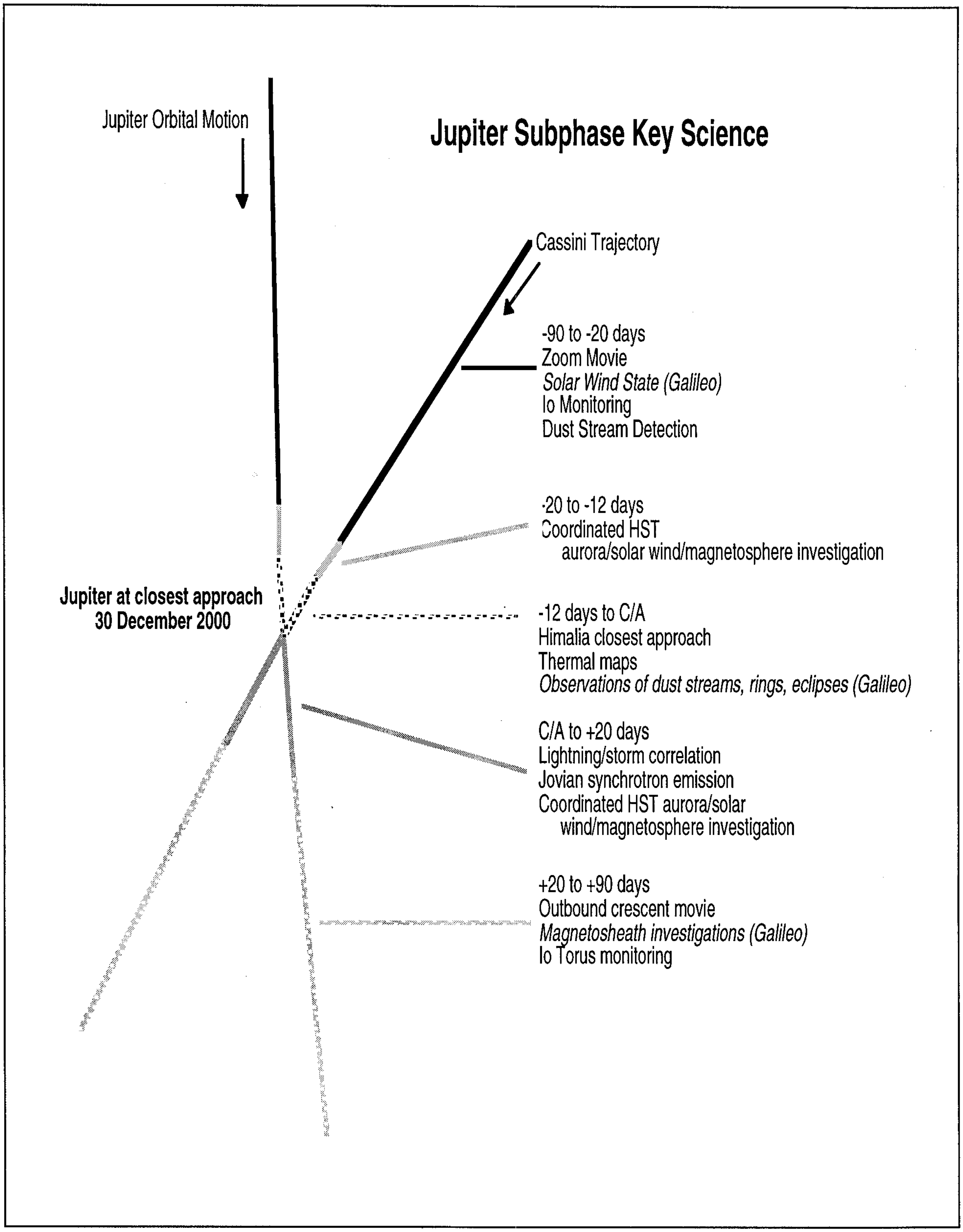

Figure 5: Jupiter Subphase Key Science

CASSINI & GALILEO ORBITS AT JUPITER

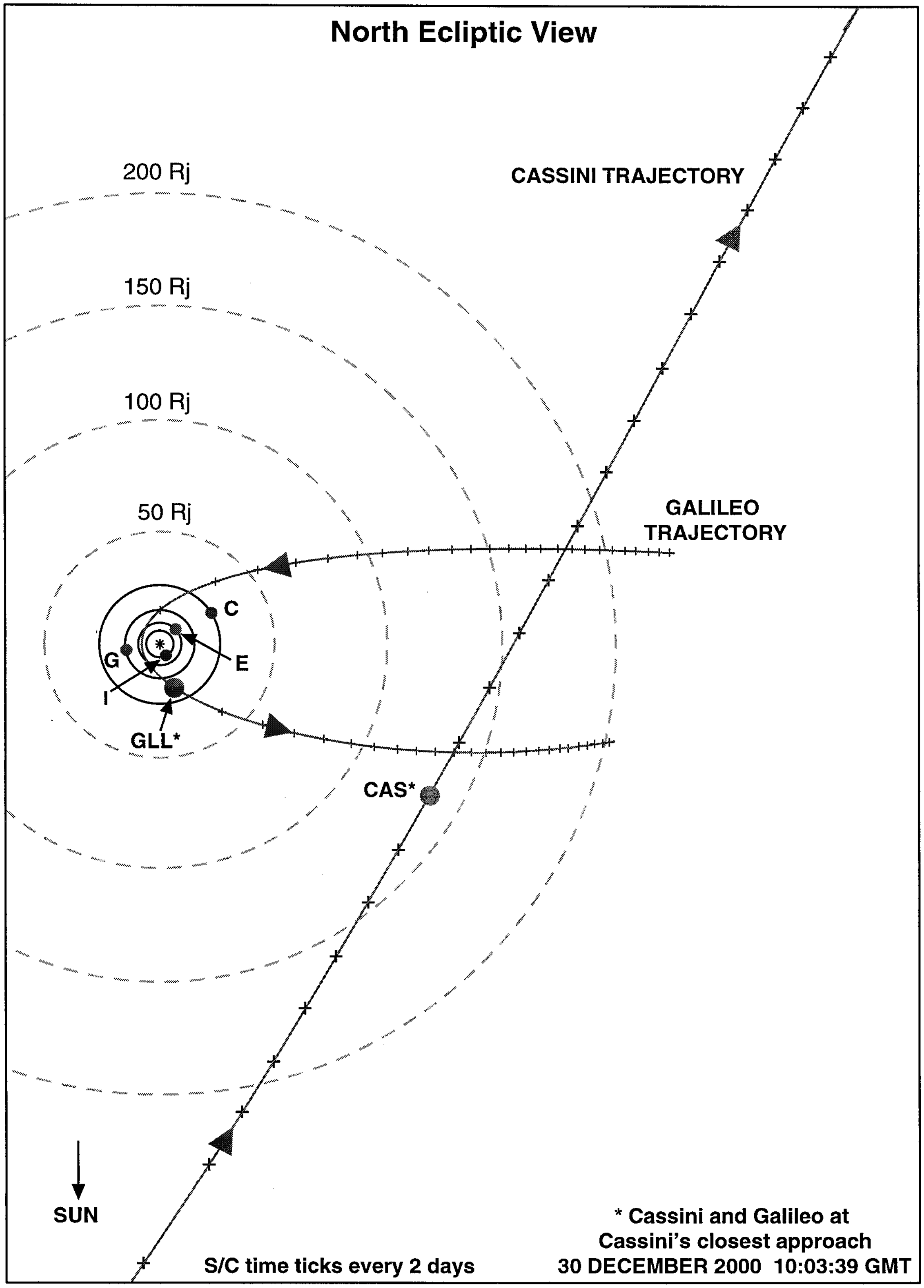

Figure 6: Cassini and Galileo Orbits At Jupiter

Mission Status Summary

The performance of the Cassini spacecraft, now three years into its nearly seven year flight time to Saturn, has been flawless. All subsystems are operating as designed, all redundant subsystems are still fully available to provide backup if needed, and all consumables are as expected, or better, to this point in the mission. Although the spacecraft has not been exercised with the intensity that will be employed at Saturn, most of the scientific instruments, most of the engineering subsystems, and the probe have been operated adequately to give a high degree of confidence that the flight hardware is up to the task before it. The primary challenge facing the Project at this point is that of being prepared to execute the mission at Saturn upon arrival. Progress to this point has been excellent and on schedule, but a substantial task remains. Flight software development continues, to provide capabilities required to accomplish the initial orbit insertion, perform the data relay with the Huygens probe, and operate in the tour. Ground software development to provide both the planning tools as well as operational capabilities is still a significant task. The overall ground system procedures and processes that will be used to implement what promises to be a very intense four years of tour operations are well on schedule for development and validation, but nevertheless represent a large effort still to be completed. In addition to this development effort, a very sizeable planning task also remains to develop the plans and strategies to be used in allocating resources to science data acquisition, and then developing the sequences necessary to implement these strategies on the spacecraft. These resources include time in the observation sequences, the attitude of the spacecraft, on-board data storage capacity, and data bits-to-ground capability. The abundance of data collection opportunities in the Saturnian system, the frequent tendency for different instruments' objectives to be mutually exclusive, and the ability of many of the instruments to generate large volumes of data combine to promise that this will be a large and challenging task for the overall Cassini team. However, the team is very experienced, capable, and motivated, and the prospects for a very rich and rewarding mission at Saturn are excellent

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Acknowledgments

The work described in this paper represents the work of the entire Cassini team, including the current flight team at JPL, a large group of scientists from across the United States and Europe, as well as the engineers and supporting staff who designed and this marvelous spacecraft to tour completion.

The preparation of this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, under contract with the National Aeronautics and Space Administration.

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